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Podocarpus lambertii wood quality for the production of long fiber pulp

Qualidade da madeira de Podocarpus lambertii visando à produção de polpa celulósica de fibra longa

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RESUMO

O setor florestal brasileiro está baseado na utilização das madeiras de *Eucalyptus* e *Pinus*, com destaque para o último no estado de Santa Catarina. Visando diversificar a base florestal para usos industriais, e fornecer informações sobre espécies que possam vir a serem alternativas, tornam-se fundamentais estudos que visem a caracterização de madeiras. Nesse sentido pode-se destacar a espécie *Podocarpus lambertii*, que é uma conífera nativa do sul do país, e que apresenta potencial de uso. Desta forma, o presente estudo teve por objetivo avaliar a qualidade da madeira de *P. lambertii* visando à produção de polpa celulósica de fibra longa. Para isso foram coletadas cinco árvores com 26 anos de idade, originárias de um plantio experimental localizado em Campo Belo do Sul/SC. Destas foram retirados discos para determinação das densidades básica e verde, composição química e análise morfológica dos traqueídeos no sentido medula-casca. As densidades básica (0,397 g/cm³) e verde (0,907 g/cm³) obtidas possibilitaram classificar a madeira como leve ou de baixa densidade. Em relação à composição química, observaram-se teores de cinzas (0,69%) e extrativos (4,40%) dentro do esperado para a madeira de coníferas, porém o teor de lignina foi elevado (36,99%), e o teor de holocelulose baixo (58,61%). As dimensões dos traqueídeos, comprimento (1,92 mm), largura (35,06 μm), diâmetro do lume (25,55 μm) e espessura da parede celular (4,75 μm), permitiram classificá-los como moderadamente longos e espessos. Os indicadores anatômicos de qualidade, fração parede (28,08%), coeficiente de flexibilidade (71,88%), índice de Runkel (0,41) e índice de enfeltramento (53,71), foram considerados muito bons para produção de polpa e papel, com base nas classificações relatadas na literatura. De modo geral, os resultados obtidos foram satisfatórios, indicando que a espécie merece atenção e estudos mais aprofundados, podendo ser uma alternativa ou complemento ao segmento de fibras longas, que hoje é abastecido exclusivamente pelo gênero *Pinus* no Brasil.

PALAVRAS-CHAVE: Pinheiro-bravo; conífera nativa; celulose e papel; propriedades da madeira.

ABSTRACT

The Brazilian forestry sector is based on the use of *Eucalyptus* and Pine wood, with emphasis on the latter in the state of Santa Catarina. Aiming to diversify the forestry base for industrial uses, and provide information on species that could be alternatives, studies aimed at characterizing wood are essential. In this sense, the species *Podocarpus lambertii* can be highlighted, which is a conifer native to the south of the country, and which has potential for use. Therefore, the present study aimed to evaluate the quality of *P. lambertii* wood with a view to producing long fiber cellulosic pulp. For this, five 26-year-old trees were collected, originating from an experimental planting located in Campo Belo do Sul/SC. Discs were removed from these to determine the basic and green densities, chemical composition and morphological analysis of the tracheids in the pith-bark direction. The basic (0.397 g/cm³) and green (0.907 g/cm³) densities obtained made it possible to classify the wood as light or low density. Regarding the chemical composition, ash (0.69%) and extractives (4.40%) contents were observed within the expected for coniferous wood, however the lignin content was high (36.99%), and low holocellulose content (58.61%). The dimensions of the tracheids, length (1.92 mm), width (35.06 μm), lumen diameter (25.55 μm) and cell wall thickness (4.75 μm), allowed them to be classified as moderately long and thick. The anatomical quality indicators, wall fraction (28.08%), flexibility coefficient (71.88%), Runkel index (0.41) and felting index (53.71), were considered very good for the pulp and paper production, based on classifications reported in the literature. In general, the results obtained were satisfactory, indicating that the species deserves attention and more in-depth studies, and could be an alternative or complement to the long fiber segment, which is currently supplied exclusively by the *Pinus* genus in Brazil.

KEYWORDS: Pinheiro-bravo; native conifer; pulp and paper; wood properties.

INTRODUCTION

The pulp and paper industry plays a crucial role in Brazil's economy. Brazil currently leads the global pulp export market, with China (39.7%) and Europe (29.7%) as its primary destinations. Additionally, Brazil ranks second worldwide in pulp production, surpassed only by the United States (IBÁ 2023).

In 2022, Brazilian pulp production grew by 10.9% compared to the previous year, reaching 25.0 million tons, demonstrating the sector's continued expansion (IBÁ 2023). Paper production in Brazil grew by 3.5% in 2022, reaching 11.0 million tons and maintaining the country's position as the world's 9th largest paper producer.

Based on the aforementioned data, the sector's continuous evolution is evident, driven by the development of new technologies and raw materials aimed at further enhancing its productive capacity. Cellulose production relies on two distinct fiber segments: short fibers derived from *Eucalyptus* species and long fibers sourced from *Pinus* species (VIVIAN et al. 2022a).

The reliance on a limited number of species may pose significant risks to the supply chain in the event of adverse conditions, underscoring the need for diversification of raw materials in the sector. This necessity justifies research aimed at evaluating the wood quality of various species that could serve as alternatives or complements for such purposes.

In this context, *Podocarpus lambertii* Klotzsch ex Endl., a conifer native to Brazil, emerges as a potential source of long-fiber wood for the timber industry. According to LONGHI et al. (1992), P. *lambertii*, commonly known as "wild pine," is well-recognized by botanists and highly valued for its quality timber. The species belongs to the Podocarpaceae family and naturally occurs in soils with varying chemical fertility, predominantly poor, well-drained, and ranging from loamy to clayey textures (CARVALHO 2004).

In order to assess the quality of wood for pulp production, it is important to know the physical, chemical and anatomical properties (ANTUNES 2009, DIAS & SIMONELLI 2013), as these will directly affect the industrial yield, cost and quality of the final product (JARDIM et al. 2017). Among the physical factors the density is highlighted, among the chemical parameters the content of cellulose, hemicellulose, lignin, extracts and ashes, and among the anatomical aspects the dimensions of the tracheides, such as length, width and thickness of cell wall (ROSA 2003, VIVIAN et al. 2021). Thus, this study aimed to assess the wood quality of P. *lambertii* for long-fiber pulp production.

MATERIAL AND METHODS

Acquisition of material

The study utilized 26-year-old *Podocarpus lambertii* Klotzsch ex Endl. wood sourced from an experimental plantation at Florestal Gateados S.A. in Campo Belo do Sul, Santa Catarina. The cultivation area was situated at an elevation of 962 meters, in a Cfb climate - humid subtropical with mild summers, according to the Köppen classification (EMBRAPA 2012).

Five trees of the species were harvested. The first log from each tree, measuring approximately 1.5 m in length and 20.0 cm in diameter at breast height (DBH = 1.30 m), was extracted and transported to the Forest Resources Laboratory at the Federal University of Santa Catarina, Curitibanos Campus, for technological characterization of the wood.

Basal discs were extracted from the logs for morphological characterization of tracheids, while discs at breast height were used for density determination. For chemical composition analysis, composite samples were prepared using surplus material from discs extracted at the base and DBH.

Basic density and green

For density determination, discs extracted at breast height were used. Two opposing wedges were prepared from these discs and submerged in water until fully saturated. Following this procedure, the saturated volume was determined according to the recommendations of NBR 11.941 from the Brazilian Association of Technical Standards (ABNT 2003). After saturation, the sample was weighed using a precision balance to determine its wet mass.

To determine the dry mass, the wedges were oven-dried at 103 ± 2°C in a forced-air circulation chamber. Based on the dry mass, wet mass, and saturated volume measurements, the basic and green densities of each of the two extracted wedges were calculated using equations 1 and 2, respectively. The average density for each tree was then determined from these values.

$$\mathrm{Db} = \frac{\mathrm{Ms}}{\mathrm{Vs}} \tag{1}$$

$$\mathrm{Dv} = \frac{\mathrm{Mu}}{\mathrm{Vs}} \tag{2}$$

In which: Bd = basic density (g/cm^3); Gd = green density (g/cm^3); Dm = dry mass (g); Wm = wet mass (g); Sv = saturated volume (cm^3).

Chemical composition

Chemical composition was determined using surplus samples from discs extracted at the base and DBH, which were processed into small chips to create a single composite sample representing all five trees. Subsequently, the wood chips were ground into sawdust using a Wiley mill and then classified with vibrating sieves, selecting the fraction retained between 40 and 60 mesh.

The analyses were conducted at the Laboratory of Chemistry, Cellulose and Energy (LQCE) of the "Luiz de Queiroz" College of Agriculture (ESALQ), University of São Paulo (USP), in Piracicaba, São Paulo. Among the parameters evaluated in triplicate are: ash content (TAPPI T 211 om-02) (TAPPI 2002), total extractives (TAPPI T 204 cm-97) (TAPPI 1997), lignin (according to the methodology adapted by LQCE/ESALQ/USP) (VIVIAN 2015). The content of holocellulose (cellulose + hemicellulose) was obtained by difference, according to Equation 3.

$$\mathrm{HC} = 100 - (\mathrm{TE} + \mathrm{TL}) \tag{3}$$

In which: HC = holocellulose content (%); TE = total extractive content (%); LC = lignin content (%).

Tracheid morphology and anatomical indicators

For the analysis of tracheid morphology and anatomical indicators, discs extracted from the base of each tree were utilized. These discs were pre-sanded to facilitate growth ring counting. After delineating the growth rings, radially oriented strips measuring 2.0 cm in width were prepared from pith to bark. From the baguettes, 5 positions were sampled: Samples were taken at 0, 25, 50, 75, and 100% of the radial distance (with 0% near the pith and 100% near the bark). Blocks were prepared from these samples and then transformed into small fragments (sticks) for maceration of cellular elements.

Maceration was performed in test tubes containing a mixture of acetic acid, nitric acid, and water (5:2:1 ratio) in a water bath at 100°C for approximately 1 hour until tracheids were individualized. Subsequently, the samples were rinsed and stored in test tubes containing distilled water.

From the macerated material, temporary slides were mounted, adding 1 drop of safranin, 1 drop of glycerin and 1 drop of water, in order to obtain images of the tracheids, at an appropriate resolution, with the aid of a microscope and magnifying glass, with a digital camera attached, and specific software for acquiring images on a computer (microscope: Leica LAS EZ; lamp: ToupView). A 6.3x magnification (using a magnifying glass) was employed for length measurements, while a 400x magnification (under a microscope) was used to capture images for width and lumen diameter measurements.

Tracheid dimensions were measured using specialized software, with 35 repetitions for each position, totaling 875 measurements (5 trees x 5 positions x 35 repetitions), following the recommendations of the International Association of Wood Anatomists (IAWA 1989). The characteristics measured were: length (L), width (W) and diameter of the fire (DF). From these measurements, cell wall thickness (T), wall fraction (WF), flexibility coefficient (FC), felting index (FI), and Runkel index (RI) were calculated using equations 4, 5, 6, 7, and 8, respectively.

$$E = \left(\frac{L - DL}{2}\right) \quad (4)$$

$$FP = \left(\frac{2.E}{L}\right).100 \quad (5)$$

$$CF = \left(\frac{DL}{L}\right).100 \quad (6)$$

$$IE = \left(\frac{C}{\frac{L}{1000}}\right) \quad (7)$$

$$IR = \left(\frac{2.E}{DL}\right) \quad (8)$$

In which: T = cell wall thickness (μm); W = tracheid width (μm); LD = lumen diameter (μm); WF = wall fraction (%); FC = flexibility coefficient (%); FI = felting index; L = tracheid length (mm); RI = Runkel index.

Data analysis

Data were stored and analyzed using spreadsheets and Sisvar statistical software (version 5.7). Initially, data normality and variance homogeneity were assessed. Descriptive statistics were used to assess density and chemical composition, while tracheid morphology was evaluated using analysis of variance (ANOVA) and Tukey's test at a 5% significance level to examine the effect of radial position (pith-to-bark) on element dimensions.

RESULTS AND DISCUSSION

Basic density and green

Table 1 presents the mean basic and green densities obtained for P. *lambertii* wood in this study, along with their respective standard deviations and coefficients of variation.

Table 1. Basic and green density of P. *lambertii* wood.

Density	Mean (g/cm³)	DP (g/cm³)	CV (%)
Basic	0,397	0,008	2,01%
Green	0,907	0,037	4,12%

In which: SD = standard deviation; VC = variation coefficient.

The mean basic density of P. *lambertii* wood at 26 years of age was 0.397 g/cm³, with low standard deviation (0.008 g/cm³) and coefficient of variation (2.01%). According to the classification system proposed by the International Association of Wood Anatomists (IAWA 1989), P*. lambertii* wood can be categorized as lightweight or low-density (< 0.40 g/cm³).

The basic density of the species in question is lower than the values reported by TRIANOSKI et al. (2013) and VIVIAN et al. (2015) for *Pinus taeda* wood, which observed values of 0.415 and 0.435 g/cm³ for 17 and 21-year-old wood, respectively. Already comparing to the values quoted by VIVIAN et al. (2022b), who evaluated P*. taeda* wood at 15 and >30 years, classified as juvenile and mature wood, with basic densities of 0.275 and 0.370 g/cm³, respectively, which are lower than those obtained for P. *lambertii*. Comparisons with P*. taeda* wood are crucial, as it is the primary species used in Brazil for long-fiber cellulosic pulp production, with factories fully adapted to its characteristics, according to VIVIAN et al. (2015).

The optimal wood density range for pulp and paper production is 0.40 to 0.55 g/cm³, categorized as light to medium density. Densities outside this range may adversely impact the pulping process (SILVA et al.). 2001, DIAS & SIMONELLI 2013). Thus, considering only the basic density parameter, P. *lambertii* wood could potentially be used for cellulose production, despite its value being slightly below the recommended range.

SEGURA (2015) and VIVIAN et al. (2020) note that understanding basic density is crucial for the efficient operation of a pulp mill, as it impacts various stages of the production process. The authors note that wood density influences log chipping, chip impregnation, and cooking processes, directly impacting pulp yield and specific wood consumption.

Regarding green density, the mean value obtained in this study (0.907 g/cm³) is lower than those reported by BONAZZA et al. (2022), which observed values of 0.966 and 1.023 g/cm³ for the wood of P. *taeda* with 9 and 21 years, respectively. This variable plays a crucial role in the timber supply and marketing process for companies and producers, as understanding it enables weight-to-volume conversions, facilitating negotiations without losses for either party (OLIVEIRA et al. 2011, VIVIAN et al. 2023). NÚÑEZ (2007) also notes that green density is used to estimate the payload of vehicles extracting and transporting timber from reforestation areas to processing facilities.

Chemical composition

The chemical composition of P. *lambertii* wood, including ash, extractives, lignin, and holocellulose content, is presented in Figure 1. The mean values obtained exhibited low standard deviation (in parentheses).

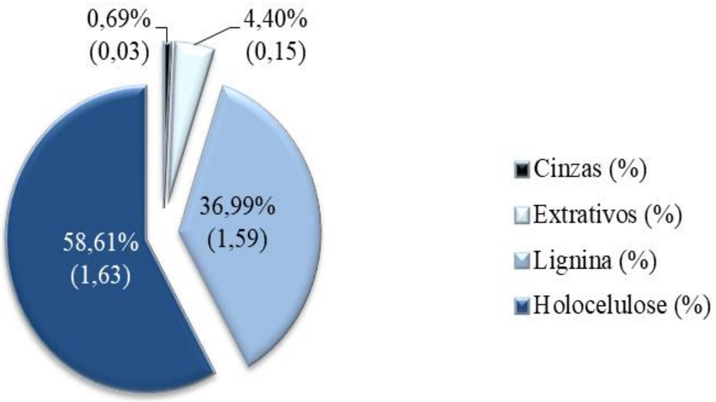


Figure 1. Chemical composition of P. *lambertii* wood.

The ash content observed for P. *lambertii* wood (0.69%), representing its inorganic fraction, aligns with the range of 0.1-1% reported by FENGEL & WEGENER (1989) for temperate species, although this value can reach up to 5% in tropical and subtropical species. The value obtained for the species in question is in the range of 0.22% (VIDRANO 2019) and 0.74% (VIANA et al. 2021) cited in the literature for the P. *taeda*.

The total extractives content found for P. *lambertii* wood (4.40%) falls within the range reported by KLOCK & ANDRADE (2013), who cite values between 5 ± 3% for conifers. The value obtained for the evaluated species exceeds the extractive content reported by VIVIAN et al. (2015) for 21-year-old P. *taeda* (2.83%), but was comparable to that reported by VASCONCELOS (2005) for 9-year-old P. *taeda* (4.50%). According to HASSEGAWA (2003), the extractive content varies due to edaphoclimatic factors, fertilization, season, and tree age, with younger individuals, having a higher proportion of earlywood, exhibiting greater quantities of extractives and lignin compared to latewood.

CARDOSO et al. (2001) and SEGURA (2012) mentioned that the pulp industry prefers wood with low ash and extractive content, as these components can lead to equipment corrosion, clogging, and pitch formation, ultimately reducing machinery lifespan and increasing maintenance costs. In this regard, it is noteworthy that P. *lambertii* wood exhibits characteristics similar to P. *taeda*, the most widely used species in Brazil for long-fiber pulp production, which is a significant finding.

The total lignin content observed in P. *lambertii* wood (36.99%) is exceptionally high, exceeding the range reported by KLOCK & ANDRADE (2013) for conifers (28 ± 2%). Previous studies have reported lignin content values for P. taeda wood ranging from 28.40% to 29.83% (VASCONCELOS (2005) and AMPESSAN et al. (2015), respectively. A species with lignin content comparable to that observed in P. *lambertii* in this study is *Cupressus lusitanica*, as reported by ALMEIDA et al. (2016), presented 36.21%.

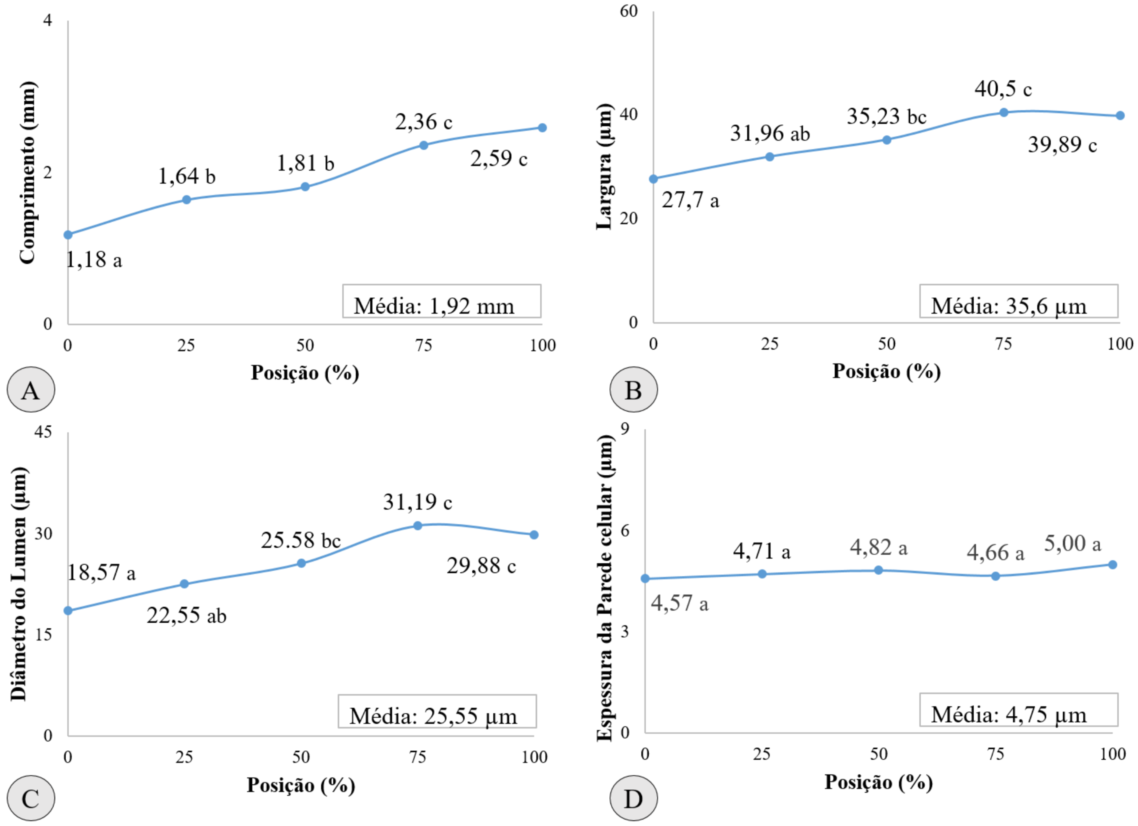
According to SEGURA (2012), high lignin content, like extractives, is undesirable in the pulping process, as it negatively impacts cellulose pulp yield and increases reagent consumption, given that one of the main objectives of the process is lignin removal. Therefore, low lignin content is desirable as it facilitates delignification, enables milder cooking conditions, and reduces fiber/tracheid degradation. In this context, the high value observed for P. *lambertii* wood was a drawback for its potential use in cellulosic pulp production. It should be noted that this is merely indicative and must be verified through pulping curves.

Finally, the holocellulose content obtained for P. *lambertii* wood (58.61%) was lower than the expected range for conifers, which according to KLOCK & ANDRADE (2013), varies between 65 and 75%. The observed value for the species is lower than that reported by AMPESSAN et al. (2015) and VIVIAN et al. (2015) for P.

taeda, reporting values of 66.17 and 70.46%, respectively. However, this is comparable to the findings reported for C. *lusitanica* (59.19%) by Almeida et al. (2016). An explanation for the low holocellulose content is the high lignin content in the wood composition of the evaluated species. FAVARO (2015) emphasizes that the holocellulose content is closely linked to pulping yield, thus the low value obtained for P. *lambertii* is a negative aspect of the species.

Tracheid morphology and anatomical indicators

Figure 2 illustrates the mean tracheid dimensions in P. *lambertii* wood across radial positions (0, 25, 50, 75, and 100%), with 0% representing the position nearest to the pith and 100% closest to the bark.



(A) length; (B) width; (C) diameter of the fire; (D) thickness of the cell wall. Different letters indicate significant variations among radial positions (Tukey p>0.05).

Figure 2. Tracheid dimensions and their radial variation for *P. lambertii* wood.

Tracheid dimensions along radial portions showed the shortest length near the pith (0% position = 1.18 mm), gradually increasing outward to reach a maximum of 2.59 mm at the 100% position. Based on the average tracheid length (1.92 mm), they can be classified as moderately long according to METCALFE & CHALK's (1983) classification system.

MARANHO et al. (2006), when studying the wood of P. *lambertii*, they obtained an average length of 2,23 mm, with a variation of 1,51 to 2,59 mm between the layers of growth. Compared to the *Pinus* genus, P. *lambertii's* tracheid length is significantly shorter, as reported by VIVIAN et al. (2015), which cite the average value of 3.50 mm for wood of P. *taeda* with 21 years of age.

Generally, tree length is the dimension most affected by age, with a tendency to increase from the pith towards the bark until stabilizing, indicating the transition from juvenile to mature wood. According to HASSEGAWA (2003), cambial activity is more rapid during juvenile wood formation and tends to stabilize during mature wood formation as the vascular cambium matures. In the wood evaluated in this study, stabilization occurred from the 75% radial position, as it did not differ statistically from the 100% position, indicating that it can already be considered mature wood. Based on the analysis of growth rings in the wood samples, the 75% position corresponded to an age of 16 years.

The width of the tracheids varied between 27.70 and 40.50 µm, with an average value of 35.06 µm. The lumen diameter ranged from 18.57 to 31.19 μm, with a mean of 25.55 μm, which is consistent with findings reported by MARANHO et al. (2006) for the same species, which was 30 μm (25,31 to 32,32 μm). Both lumen width and diameter increased significantly from pith to bark.

The average cell wall thickness was 4.75 μm, which closely aligns with the findings reported by MARANHO et al. According to MANIMEKALAI et al. (2006), the approximately 5.0 μm thick layer showed no significant radial variation in either case and can be classified as thick, according to MANIMEKALAI et al. (2002).

When compared to the genus *Pinus*, P. *lambertii* exhibits smaller tracheid width, lumen diameter, and wall thickness than those reported by VIVIAN et al. (2015) For 21-year-old P*. taeda* wood, the values were 40.55, 27.71, and 6.41 μm, respectively.

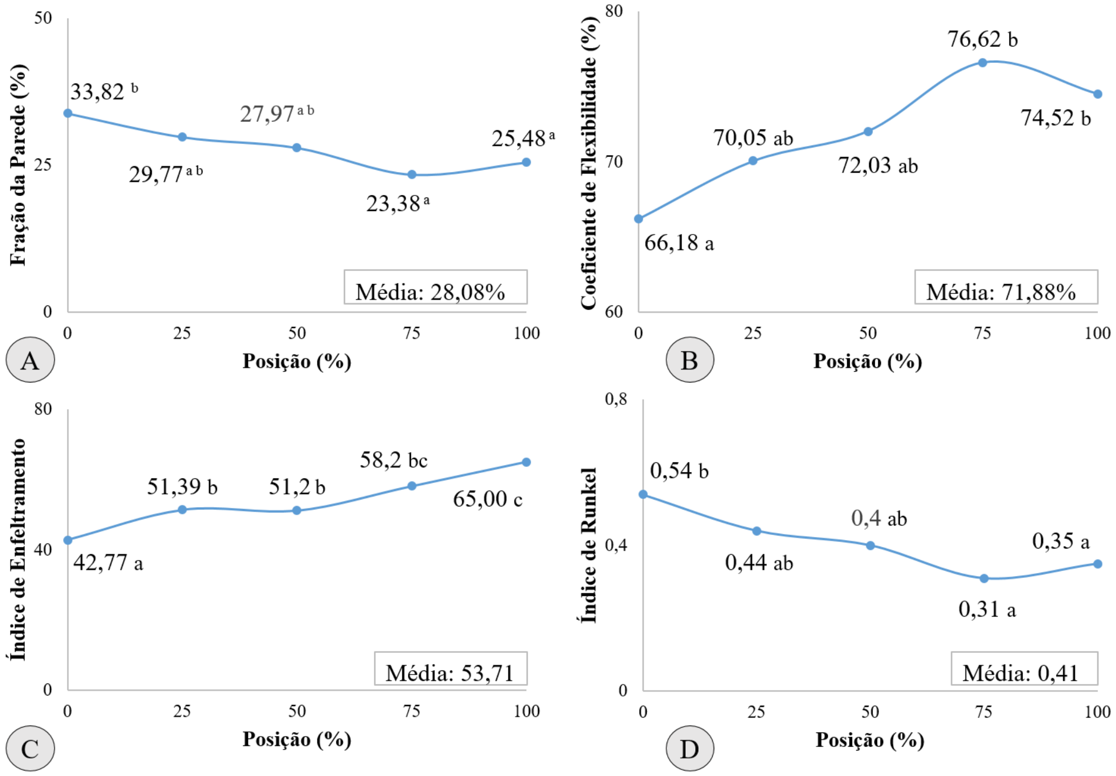
Figure 3 illustrates the variation in wood quality parameters for P. *lambertii* across radial positions (0, 25, 50, 75, and 100%).

The wall fraction exhibited a mean value of 28.08% (with significant variation between 23.38% and 33.82%), which can be classified as thin and low-rigidity according to KLOCK (2013). BALDIN et al. (2017) noted that the optimal wall fraction should be below 40%, as this facilitates fiber collapse during paper formation, resulting in stronger inter-fiber bonds. According to these authors, pulps derived from species with thin-walled fibers/tracheids yield higher pulping efficiency and produce paper with superior tensile strength, burst resistance, tear resistance, folding endurance, surface strength, and internal bonding.

The flexibility coefficient exhibited a mean value of 71.88% (significant variation between 66.18% and 76.62%), which, according to NISGOSKI's (2005) classification, indicates tracheids with good contact surface and strong inter-tracheid bonding, accompanied by partial collapse. According to SHIMOYAMA & WIECHETECK (1993) and VIVIAN et al. (2015) the flexibility coefficient indicates the degree of flattening experienced by fibers/tracheids during paper manufacturing. Higher coefficient values suggest greater fiber flexibility, increasing the likelihood of inter-fiber bonding and resulting in enhanced tensile and burst strength.

The Runkel ratio averaged 0.41 (significantly varying from 0.31 to 0.54 in the radial direction), suggesting that P. *lambertii* wood tracheids can be classified as excellent for papermaking, according to Runkel's criteria as cited by TOSTES et al. (2013), falling within Group II (between 0.25 and 0.50).

VIVIAN et al. (2020) cited that the Runkel index indicates the degree of fiber or tracheid collapse during papermaking. A lower index suggests greater collapse, enabling fibers to have more contact surface area and form more inter-fiber bonds, resulting in paper with higher tensile and burst strength.



(A) wall fraction; (B) coefficient of flexibility; (C) Runkel index; (D) infiltration index. Different letters indicate significant variations among radial positions (Tukey, p>0.05).

Figure 3. Anatomical indicators and their radial variation for *P. lambertii* wood.

Finally, the felting index exhibited a mean value of 53.71 (ranging significantly from 42.77 to 65.00), exceeding the minimum threshold of 50 required for fibers to possess sufficient flexibility for use in the pulp and paper industry, thereby imparting desirable characteristics to the produced paper, as reported by NISGOSKI (2005).

Among the observed species, P. *taeda* wood is the most commonly used in long-fiber paper production, with its values serving as the primary benchmarks in this context. Thus, the values obtained for wall fraction (28.08%), flexibility coefficient (71.88%), and Runkel index (0.41) for P. *lambertii* wood were comparable to or even superior to those reported by VIVIAN et al. (2015) for P. *taeda* (32,00%; 68,00% and 0,46, respectively).

The anatomical features of P. *lambertii* wood tracheids are promising for cellulosic pulp production. Further research on its pulping curves and paper production behavior is warranted to explore its potential as a novel alternative or complement to long-fiber cellulosic pulp production.

A crucial consideration is the slow growth rate of P. *lambertii*, particularly when compared to *Pinus*, currently the most widely cultivated conifer in Brazil. It is worth noting that the material evaluated in this study had not undergone genetic improvement, suggesting significant potential for future advancements in this area.

CONCLUSION

Based on the results obtained for 26-year-old P. *lambertii* wood, it is concluded that this species has a low density, approaching the minimum threshold required by the industry for cellulosic pulp production. The chemical composition aligns closely with expectations for coniferous wood, particularly regarding ash and extractive content. However, the elevated lignin levels and reduced holocellulose content may adversely affect cellulosic pulp production processes. Tracheid dimensions, including length, width, lumen diameter, and cell wall thickness, indicate moderate length and thickness, with values lower than those reported for P. *taeda*. The anatomical quality indicators, including wall fraction, flexibility coefficient, Runkel index, and felting index, are considered highly favorable for pulp and paper production, according to classifications reported in the literature.

The results obtained for P. *lambertii* wood were promising, with the exception of high lignin content and low holocellulose content. Other parameters suggest that this species warrants further investigation as a potential alternative or complement to long-fiber sources, currently supplied exclusively by *Pinus* species in Brazil. Another noteworthy aspect is that the evaluated species has not undergone genetic improvement, suggesting potential for enhancing its properties through selection and forest breeding programs.

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